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Revision -

INFO

ICESat Observatory Timing Overview

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1. Introduction

This report describes the timing scheme used by the ICESat observatory and shows how the precise times of events on the observatory can be reconstructed from the downlinked telemetry. Section 3 presents an overview of the time scheme used by ICESat. This is followed by more detail on the time scheme implementation for GLAS (Geoscience Laser Altimeter System) and the bus. (Sections 4 and 5 respectively). Section 6 contains descriptions of how observatory events critical to science are timestamped and the relationship of those events to GPS receiver time. Appendix A contains a list of definitions used throughout this paper. Appendix B describes the flow of packets throughout the observatory, and finally Appendix C presents an outline of the timing validation and verification scheme.

Change Log

2. Referenced Documents

- BASD Dwg. 545607 - "RS2000 Spacecraft to GLAS Instrument Interface Control Document"
- BASD Dwg. 545586 - "RS2000 Spacecraft to SRS Interface Control Document"
- BASD SER3257-SYS086A - "ICESat, Spacecraft Bus Timing Description"
- ICES-401-ICD-001 - "BlackJack (BJ) Global Positioning System (GPS) Receiver Interface Control Document (ICD) for the Ice, Clouds, and Land Elevation Satellite (ICESat)"
- GLAS Timing Workshop Notes - E. Ketchum
- Ice, Clouds, and Land Elevation Satellite Geoscience Laser Altimeter System (GLAS) Instrument Description Document - February 15, 1999

3. Time Scheme Overview

3.1 Introduction

Determination of the precise time of events on the ICESat mission is based on a tiered scheme with GPS time at the top defined as the primary time scale. The next layer below GPS in accuracy are the secondary time schemes maintained in both GLAS and the Ball RS2000 bus. Tertiary time schemes are also maintained in subsystems of both GLAS and the RS2000. This section presents an overview of the time schemes beginning with the implementation of GPS time and followed by the secondary and tertiary schemes.

3.2 GPS Time

GPS time is determined on orbit by redundant JPL/SpectrumAstro BlackJack (BJ) GPS receivers. The GPS control segment attempts to keep GPS time to within 1 microsecond of UTC (USNO) discounting for the effect of leap seconds. Each GPS receiver provides a precise timing pulse at 10 second intervals to both the GLAS Main Electronics Unit (MEU), and the redundant Spacecraft Control Computers (SCC) in the RS2000 bus. Also, each GPS receiver issues a correction value from which GPS receiver time is offset from GPS system time to within an accuracy of 1 microsecond. The GPS receiver time associated with the timing pulse is contained in the PPSTime packet issued by the receiver no later than 8 seconds after the pulse and before the next pulse. The correction value is contained in the AntennaState packet issued, except as noted below, after the pulse with which it is associated and before the next pulse. The GPS time pulse is produced coincident with the GPS minute (e.g. 23:00:00, 23:00:10, 23:00:20, ….).

Each BlackJack GPS receiver generates a 0.1 Hz timing pulse having a width of 1.8 microseconds, and with rise and fall times of less than 10 nanoseconds. When a receiver is first powered up or reset after a fault condition, the timing pulse will not be present until after the AntennaState packets are being generated. This requires that a minimum of four (4) SVs be tracked. The timing pulse is an unambiguous time indication to GLAS and the bus that steady-state navigation has been achieved.

All GPS data is time tagged against the receiver clock which is based on an internal quartz oscillator. The oscillator drives a counter that counts seconds after some initial epoch. The oscillation frequency is constantly readjusted so that the oscillator drift is nearly zero. This adjustment is based upon the time offset contained in the antenna state packet. This is called clock steering. The time offset is the difference between when the pulse occurred and when the pulse was supposed to occur. When there is no data for a navigation solution, there is no clock steering. Clock steering occurs when there are at least five (5) satellites being tracked and the chi-square value is between 0.01 and 10,000 indicating a valid solution. After the receiver has been tracking five or more GPS satellites for about one hour, the receiver time will be steered to within approximately 20 microseconds of GPS time. No steering is applied if the receiver clock is within 2 microseconds of GPS time. During outages, timing pulses with their associated PPSTime packets will continue to be issued based on the GPS receiver clock; however, the relation of the pulses with respect to GPS system time will drift.

3.3 Secondary Time Schemes

ICESat maintains two secondary time scales: GLAS time which is based on a stable 2 GHz Master Oscillator in the GLAS Main Electronics Unit (MEU), and Bus time based on a Precision External Clock (PEC) located in the RS2000 bus. Both time scales are implemented using oven controlled quartz oscillators.

The Master Oscillator in the GLAS instrument drives a 40-bit Master Counter at 15.625 MHz, and the value of that counter at any given instant is the GLAS Vehicle Time Code Word (GVTCW). The value of the Master Counter rolls over every 19.54687 hours.

The PEC drives a 48-bit counter at 1.0 MHz and the value of that counter at any given instant is the Bus Vehicle Time Code Word (BVTCW). The value of the BVTCW counter rolls over every 8.9255 years.

By time stamping the arrival of the 0.1 Hz pulse from the GPS receivers, both GLAS through the GVTCW and the Bus though the BVTCW can relate appropriately time stamped events to GPS time. Both the GVTCW and the BVTCW may be reset to zero on power up or re-boot.

3.4 Tertiary Schemes

Both GLAS and the Bus maintain lower accuracy time schemes within specific subsystems. For instance, the Instrument Processing System (IPS) in GLAS maintains a Mission Elapsed Time (MET) incremented at 25 millisecond intervals. In addition, both the Instrument Star Tracker, the Laser Reference System, and the Litton Inertial Reference Unit (both located in the Stellar Reference System) all maintain internal clocks.

The Bus maintains a time scheme term Bus UTC (BUTC) which is used by parts of the attitude control system which do not require great accuracy. It has no impact on ICESat science data processing.

3.5 ICESat Timing Relations

Figure 1 below illustrates the relations between the time schemes. On the GLAS side, the Frequency and Time section of the Cloud Digitizer board receives the 0.1 Hz pulse from the GPS receiver and time stamps it with the Master Counter. This section also takes in the clock signal from the Master Oscillator and converts into the 40 Hz pulse used to fire the lasers and trigger the Laser Profiling Array (LPA). The 40 Hz clock signal is also divided down into a 10 Hz synchronization signal used by the Instrument Star Tracker (IST) and Laser Reference System (LRS).

On the RS2000 bus, the GPS 0.1 Hz pulse is timestamped by the board in the SCC which maintains the BVTCW. Asynchronous to the 0.1 Hz GPS pulse, the SCC will do the following. On one second intervals, it will issue a Position, Rate, Attitude (PRA) packet to the Science Data Formatter (SDF). Asynchronous to the PRA packet and also on one second intervals, the SCC will send a packet to the GLAS MEU which includes BVTCW to within 100 ms of when the estimated position was calculated, the GPS receiver time, and the BVTCW associated with the GPS receiver time.

At 100 millisecond intervals (10 Hz), the SCC will issue data request to the Ball star trackers (BST), the space inertial reference unit (SIRU), the ROSI Instrument Star Tracker (IST), and the ROSI Laser Reference Sensor (LRS). These data requests are asynchronous to the 10 Hz pulses from the GLAS MEU.

The GPS receivers send a packet stream to both the SCC and the SDF. The stream sent to the SCC is a limited set of packets that includes:

1. PPSTime
2. AntennaState
3. Command responses

The packets listed above are sent with every 0.1 Hz pulse when four or more GPS SV's are in sight and trackable. Others such as GetDir and Command Ack are sent only when necessary. The packet set sent to the SDF includes the ones sent to the SCC plus QuadraticFitObservables and others that are needed only in post-processing the science data.

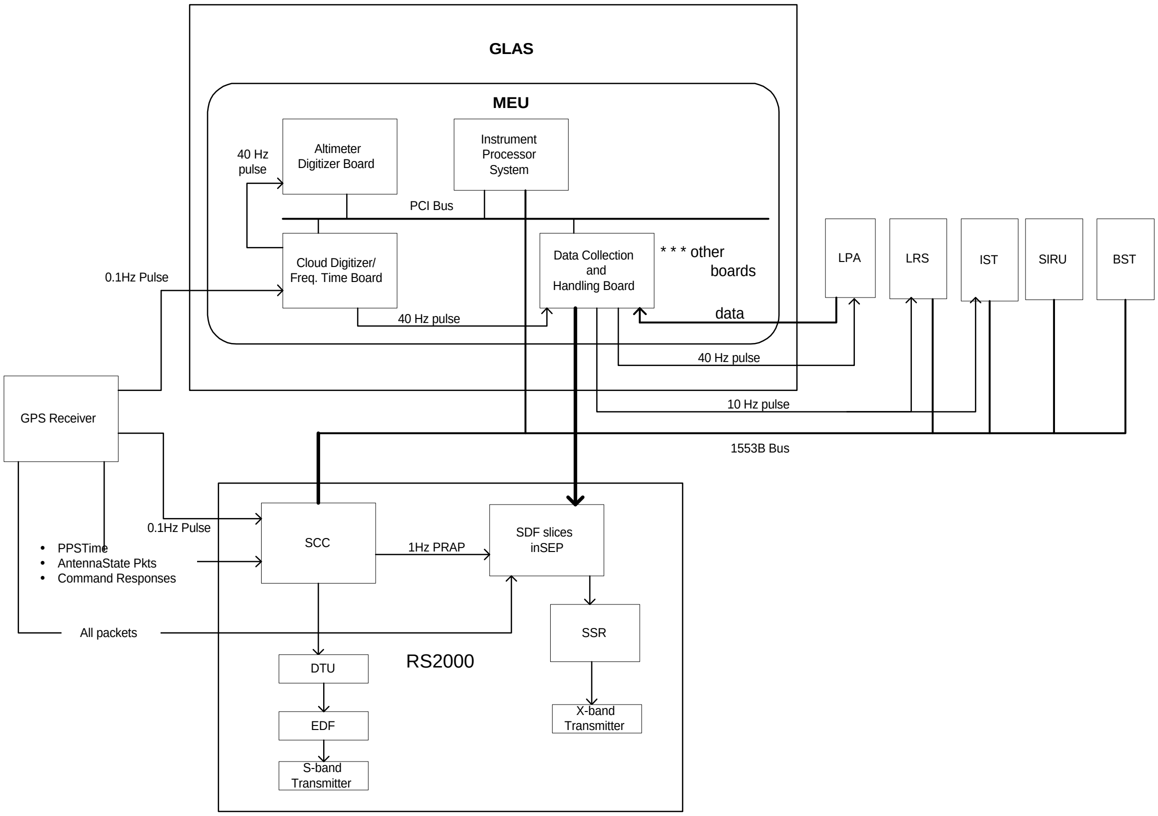

Figure 1 Observatory Timing Overview

4. GLAS Overview

Critical event initiation and timing in the GLAS instrument is defined by the 2 GHz Master Oscillator which drives three main divider chains (see Figure 2). The laser firing chain divides the 2 GHz down to a 40 Hz clock which is used to initiate firing the active laser and start a data capture sequence in the Laser Profiling Array. The 40 Hz clock is further divided down to a 10 Hz clock which is used as the synchronization for the ROSI Instrument Star Tracker (IST) and the Laser Reference System (LRS).

The second chain, the time stamp chain, has the 2 GHz clock divided down to 15.625 MHz which then drives the 40-bit counter. The 40 Hz fire command (clock), fire acknowledge, and the GPS timing pulse each strobe their own latches. The actual firing of the laser is accomplished via a software command triggered by the 40 Hz fire command. Individual laser shots are tagged at 40 Hz using an 8-bit counter that ranges in value from 0 to 199. The 15.625 MHz clock is further divided by 8 into a 1.953125 MHz signal that drives the analog-to-digital converter in the Cloud Digitizer board and the logic in the Photon Counter board.

The third chain divides the 2 GHz clock by two in order to drive the Altimeter Digitizer A/D converter at 1 Gsamples/sec . The 1 GHz signal is further divided to provide several high speed clocks to manage the data from the sampled signal. The Digital Signal Processor on the back end of the Altimeter Digitizer has its own 25 MHz clock which does not factor into the precise timing of science data.

Data from the Laser Reference System and the Instrument Star Tracker are passed to the SCC over the 1553B bus. The SCC then packages this and other data into the PRA (Position, Rate, Attitude) packet which it sends to the Science Data Formatter (SDF) at one second intervals. The Laser Profiling Array data is processed by the Data Communication and Handling Board (DCHB) into a CCSDS source packet and sent to the SDF. All other data is processed by the Instrument Processing System (IPS) and then sent to the DCHB for transmission to the SDF.

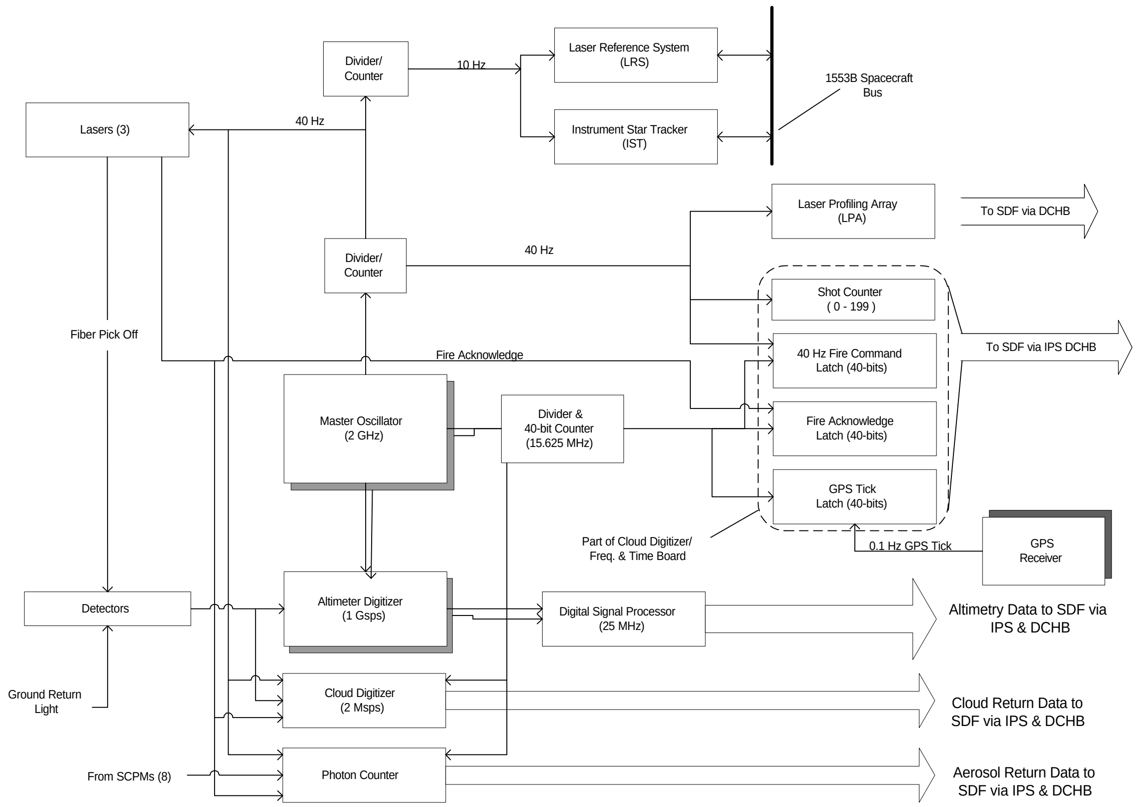

Figure 2 GLAS Timing Signal Overview

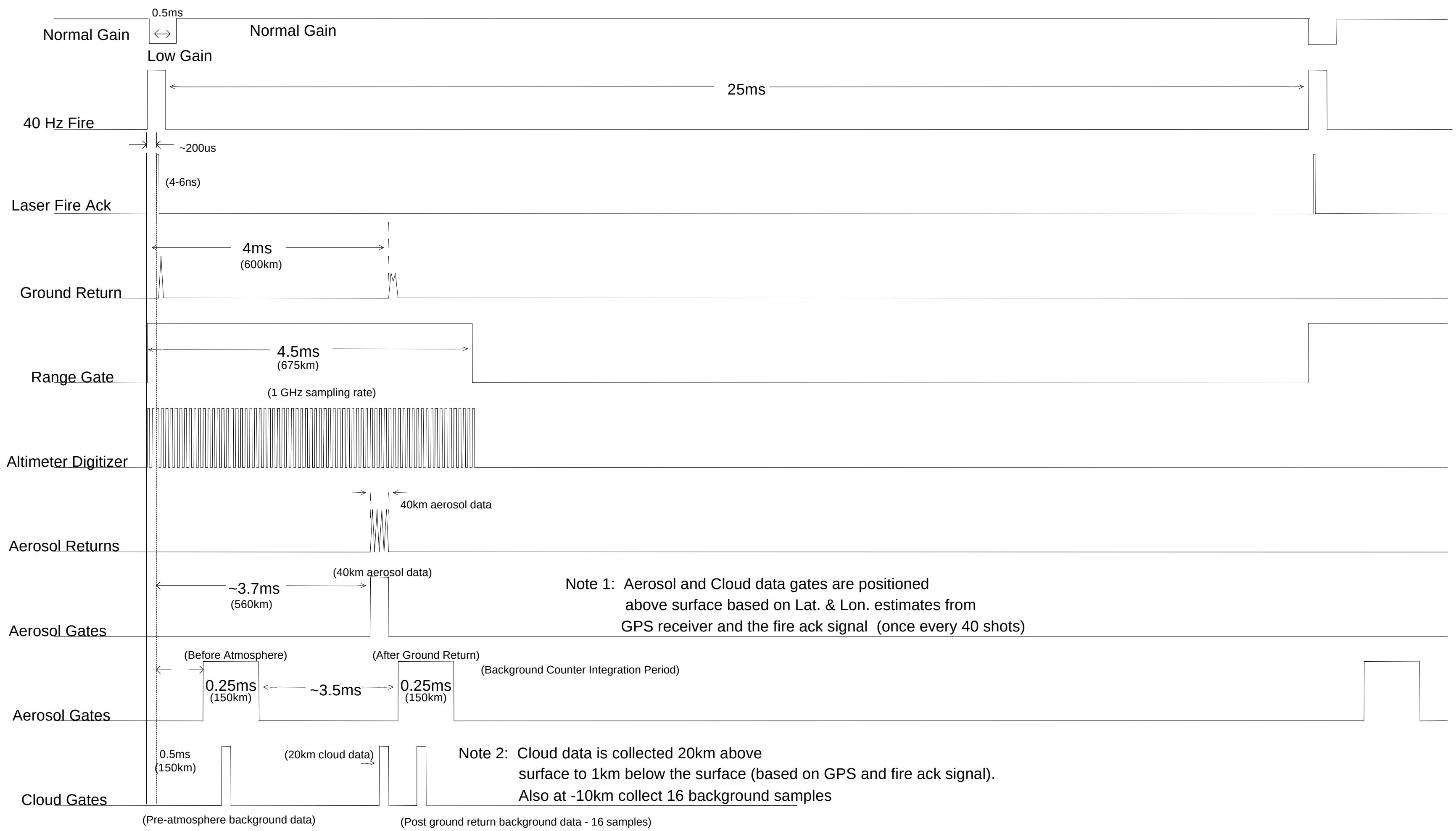

Figure 3 GLAS Event Timing

Figure 3 above illustrates the relationships between the events in a single 25 millisecond laser firing sequence. The sequence of events begins with a 40 Hz Fire Command. To prevent saturation of the detectors, their gain state is set to low for 500 microseconds at the leading edge of the pulse. Some 200 microseconds after the leading edge of the fire command, the Fire Acknowledge signal should be received. The Ground Return track shows when the signal from the optical fiber pickoff in the laser will be received and when the ground return is expected (about 4 milliseconds). A Range Gate limits operation of the GLAS receiver to minimize the chance of damage and false data collection.

The Altimeter Digitizer samples the returned signal while the Range Gate is active. This includes both the fiber pickoff as well as the ground return. The pickoff is digitized to allow centroiding of the 4-6 ns pulse shape.

In contrast, the 532 nm Aerosol Returns are measured at three points. The first measurement is at about 2.7 msec after the laser fire for pre-atmosphere background calibration. At this time the gate will be open for 256 microseconds collecting scattering data from a 76.8 km column from about 195 km to about 118 km above the surface. During the second mesurement the gate is opened to collect data from about 40 km above the surface to 1 km below the expected surface. The timing for this gate is driven by a Digital Elevation Map (DEM) map in GLAS which determines the latitude and longitude based on input from the GPS receiver. The third and final measurement is also used for calibration and occurs after the final ground return about 4.2 milliseconds after the fire command. The gate is active for 256 microseconds.

The Cloud Digitizer is started by the Fire Ack signal and is active for background data at the same times as the Aerosol Gates. For this channel, however, the background gates are active for only 128 microseconds. While the Cloud Digitizer and Photon Counter boards are designed to begin sampling at 41 km, the software only collects and telemeters data from about 21 km above the surface to 1 km below the expected surface. The timing for this gate is driven by a DEM map in GLAS which determines the latitude and longitude based on input from the GPS receiver. Both Cloud and Aerosol data are sampled at 1.95325 MHz.

5. RS2000 Bus Overview

Critical event initiation and timing on the RS2000 bus is tracked using a Vehicle Time Code Word (BVTCW). The BVTCW is maintained by a 48-bit hardware counter that starts at zero, counts to 2^{48}-1, and then resets to zero. Since each bit represents one microsecond, the counter will roll over approximately every 8.925 years. The counter is maintained in the Spacecraft Control Computer and is driven by the 1 MHz PEC. Each SCC has its own PEC.

Whenever the SCC is reset, the BVTCW counter is reset to zero. The BVTCW can be set to a given value by ground command. Also, the flight software can latch and read the value of the BVTCW counter on command.

The BVTCW is used to time tag all delayed commands uploaded from the ground. These commands are stored in the Command Storage Memory (CSM). Every 200 milliseconds, the flight software compares the current BVTCW to the command time tags of the commands in the CSM to determine if the individual commands should be executed or not. For each time entry, the flight software subtracts the command's BVTCW time tag from the current value of BVTCW. If the difference is between 0 and 300 milliseconds, the flight software will execute the command, and mark it as executed. If the time tag is greater than 300 milliseconds in the past, the command will be marked as bypassed and not executed. In addition to command time tagging, the BVTCW is used to time tag the attitude control cycle data, and is used as a master reference by the flight software.

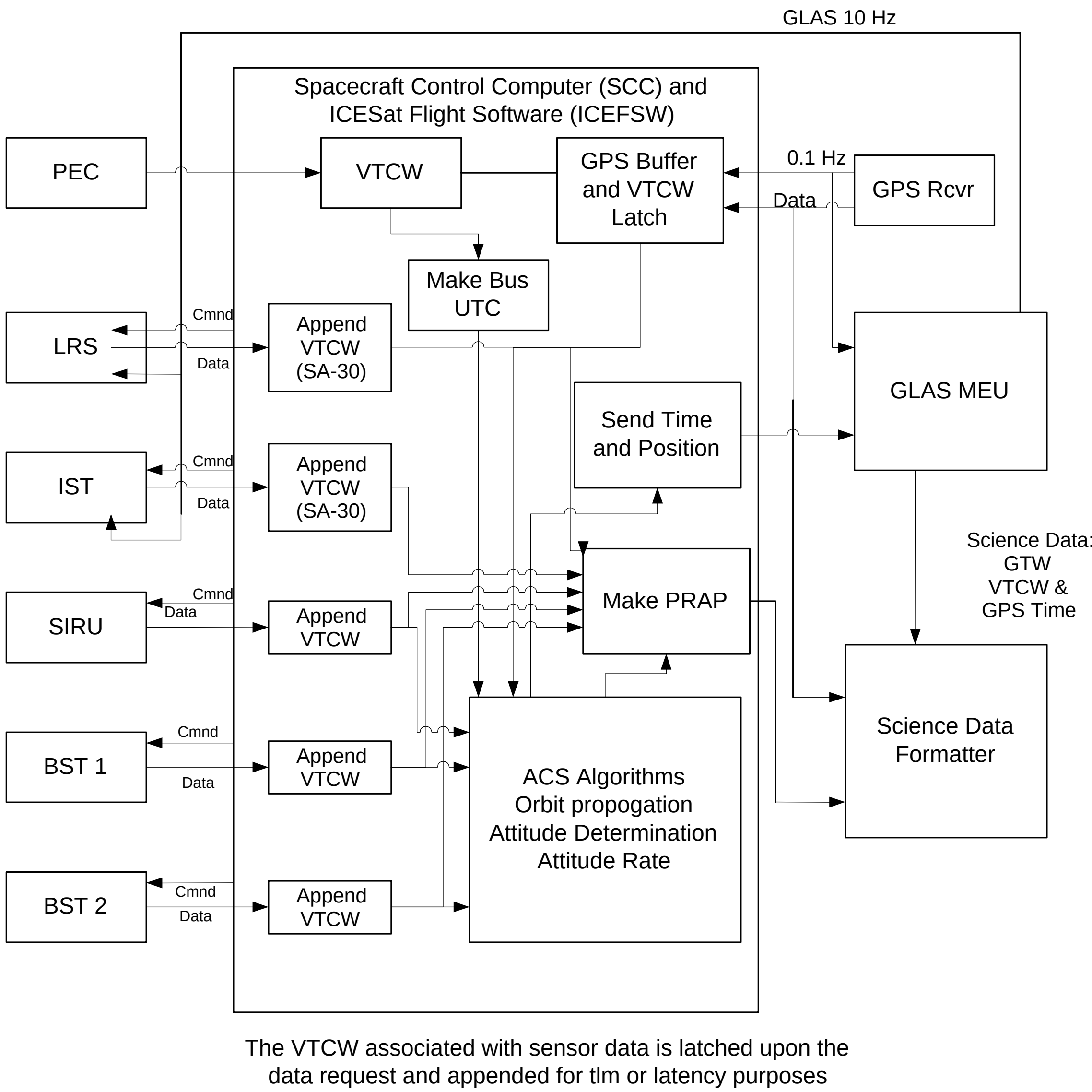

Figure 4 RS2000 Bus Timing Overview

The ICEFSW will configure SCC hardware timers so as to generate a 5 Hz pulse. (This may be changed to a higher frequency in the design.) Basic software operations are keyed to this highest frequency loop timer. Slower frequency tasking is handled within the software by keeping track of how many cycles have been executed.

Once every ten seconds, the SCC will receive a pulse from the GPS receiver. This happens asynchronously with the 5 Hz timer pulses within the SCC. In conjunction with receipt of the 0.1 Hz GPS pulse, the SCC hardware will latch the BVTCW. Shortly thereafter, the GPS will send its position and rate solution and its GPS receiver time via an RS422 interface to a hardware buffer in the SCC. The GPS data, including GPS receiver time corresponds to the 0.1 Hz pulse just previously received to within 1.5 microsecond with respect to the leading edge of the pulse from the GPS.

5.1 ACS Timing

The present estimate of spacecraft position is maintained by the ADCS algorithms. The flight software feeds the GPS position and velocity information into the onboard orbit propagator which does two things. It filters raw position and velocity GPS updates with an onboard dynamics model. In this manner, the propagator prediction of present position is better than raw data from the GPS receiver. The orbit propagator updates spacecraft position internal to the flight software every 15 seconds and interpolation functions fill in the times between propagator updates at a 5 Hz rate, i.e. position is predicted for the start of the next 5 Hz cycle.

For contingency operations the propagator can also predict position and velocity without using GPS data. This can be done for extended periods with degraded performance.

For the purpose of on-board position, attitude and rate determination the timing of the propagator and sensor data is kept track of by appending BVTCW to the samples of data. In the case of the bus star trackers, the software also accounts for the latency of the data.

5.2 Bus Transmission of Time Stamped Science

Once per second, the SCC sends a time and position message to GLAS. The transmission includes:

- BVTCW to within 100 ms of when the estimate position was calculated.
- The estimate of spacecraft position associated with the BVTCW.
- GPS receiver time and time offset.

Once per second, the flight software loads an output buffer with Position, Rate and Attitude (PRA) Packet. Under Science Data Formatter control, the PRA packets are retrieved in 8192 bytes blocks from the output buffer. These blocks are interleaved with the Science and GPS data from other sources into the data stream that is sent to the solid state recorder, and from there to the X-Band down-link.

The PRAP includes:

a. BVTCW, loosely corresponding to the time at which the PRAP message is put into the SDF buffer (1 Hz)
b. SIRU data, including BVTCW time stamp (10 Hz)
c. BST #1, including BVTCW time stamp (10 Hz)
d. BST #2, including BVTCW time stamp (10 Hz)
e. IST data, including BVTCW time stamp (10 Hz)
f. LRS data, including BVTCW time stamp (10 Hz)
g. LRS star image (5 Hz)
h. LRS laser image (4 Hz)
i. LRS CRS image (1 Hz)
j. The estimate of the spacecraft position (1 Hz)
k. The estimate of the spacecraft attitude and rate quaternions (1 Hz)
l. Solar Array Position (1 Hz)

5.3 Bus Collection of Time Stamped Science

The bus collects data from several sensors which is used both for accurate real-time pointing as well as precision attitude determination during post processing. The sensors are:

a. (2) Ball Star Trackers (BST)
b. (1) Litton Space Inertial Reference Unit (SIRU)
c. (1) Instrument Star Tracker (IST)
d. (1) Laser Reference System (LRS)

The accurate correlation of sensor data collected by the bus is described in Section 7.0

6. Events, Timing and Reconstruction to GPS Time

This section describes how events on the observatory critical to science can be precisely related to GPS time. Table 1 lists the events, where they occur, and their rate.

Table 1 Observatory Science Events

Unit	Rate (Hz)	Event
Bus	0.1	• BVTCW time stamp • Capture GPS PPSTime and AntennaState packets from GPS
Bus	1	• BVTCW to IST • BVTCW to LRS • Time and Position message to GLAS MEU • PRAP to SDF
Bus	5	• ACS computations • Laser Reference System Pixel Sample (5 Hz, 4 Hz, 1 Hz)
Bus	10	• SIRU Data Sample • Instrument Star Tracker Centroid Data Sample • Laser Reference System Centroid Data Sample • Bus Star Tracker Data Sample
GLAS	0.1	• GVTCW time stamp
GLAS	1	• Capture time and position packet from bus
GLAS	10	• Instrument Star Tracker Synchronization Pulse • Laser Reference System Synchronization Pulse
GLAS	40	• Laser Fire • Fire Acknowledge • Altimeter Channel Data Sample • Cloud Channel Data Sample • Aerosol Channel Data Sample • LPA Data Sample
GPS	0.1	• GPS timing pulse • Port 1: PPSTime, AntennaState, command response packets • Port 2: all packets

6.1 GPS 0.1 Hz Events

During normal operation the GPS receiver will issue a GPS Timing pulse every 10 seconds. The difference between GPS time and GPS receiver time is contained in the TimeOffset field of the AntennaState packet.

Reconstruction to GPS: Add the value of the TimeOffset field in the AntennaState packet to the GPS receiver time contained in the PPSTime packet to produce GPS system time.

6.2 Bus 0.1 Hz Events

The bus will time stamp the receipt of the 0.1 Hz GPS Timing pulse with the BVTCW at the time of the pulse. This time value is labeled $BVTCW_{0.1}$. Shortly after the receipt of the GPS Timing pulse, the bus will receive the PPSTime, and AntennaState packets from the GPS receiver. These packets will reflect time at the GPS timing pulse.

Reconstruction to GPS: Add TimeOffset in the AntennaState packet to PPSTime in the Time packet to produce $GPSTime_{0.1}$ at $BVTCW_{0.1}$. Until the next GPS Timing pulse, the value of GPS system time for a given BVTCW is:

$$GPSTime = GPSTime_{0.1} + (BVTCW - BVTCW_{0.1} + d) * 1.0e\text{-}6$$

where the constant 1.0e-6 reflects the PEC clock rate of 1 MHz. δ is a measured correction value that accounts for delays between the receiver and the time stamp latch.

6.3 Bus 1 Hz Events

6.3.1 VCTW to IST

At one second intervals, the BVCTW will be sent to the Instrument Star Tracker over the 1553B bus. The BVCTW will reflect the time the value is sent and will have a transmission latency of <12.5 milliseconds. This will allow the ground processing software to determine the 40 Hz laser firing command that coincides with the 10 Hz synchronization signal from the GLAS MEU to the IST.

Reconstruction to GPS: See Instrument Star Tracker Data Sample (section 6.5.3)

6.3.2 VCTW to LRS

At one second intervals, the BVCTW will be sent to the Laser Reference System over the 1553B bus. The BVCTW will reflect the time the value is sent and will have a transmission latency of <12.5 milliseconds. This will allow the ground processing software to determine the 40 Hz laser firing command that coincides with the 10 Hz synchronization signal from the GLAS MEU to the LRS.

Reconstruction to GPS: See Laser Reference System Data Sample (section 6.5.4)

6.3.3 Time and Position message to GLAS

At one second intervals, the SCC sends a Time and Position message to the GLAS MEU over the 1553B bus. The message contains:

1. BVTCW to within 100 milliseconds of when the estimated position was calculated
2. Estimated position (ECEF in km X,Y,Y) associated with BVTCW
3. GPS receiver time at the last GPS timing pulse
4. BVTCW at the last GPS timing pulse.

Reconstruction to GPS: This information is used by GLAS in real-time to determine the position in the DEM for laser range gating. It is not used for precise attitude or position determination.

6.3.4 PRA Packet to Science Data Formatter

At one second intervals, the SCC sends a Position, Rate and Attitude packet (PRAP) to the Science Data Formatter containing the following (per SER 086A):

a. BVTCW corresponding roughly to the PRAP transmission time (1 Hz)
b. SIRU data including BVTCW time stamp (10 Hz)
c. BST #1 data including BVTCW time stamp (10 Hz)
d. BST #2 data including BVTCW time stamp (10 Hz)
e. IST data including BVTCW time stamp returned from IST (10 Hz)
f. IST health data (1 Hz)
g. LRS data including BVTCW time stamp returned from LRS (10 Hz)
h. LRS health data (1 Hz)
i. LRS star image (5 Hz)
j. LRS laser image (4 Hz)
k. LRS CRS image (1 Hz)
l. Estimate of spacecraft position (1 Hz)
m. Estimate of spacecraft attitude and rate (1 Hz)
n. Solar array position

Reconstruction to GPS: The SDF uses the BVTCW for this message (item a) as part of the header for its CCSDS packet. The purpose of this is to keep the packets in order of receipt, not for time correlation.

The on-board estimates of Position, Attitude Rate and Attitude as computed by the ADCS are relatively coarse as compared to the precision determination to be accomplished as part of the science data processing.

Data from the sensors will be used for precision attitude determination in conjunction with science data processing on the ground. Each of these devices has a BVTCW time stamp associated with its measurements (see section 6.5).

6.4 Bus 5 Hz Events

6.4.1 ADCS Algorithms

At 200 millisecond intervals, the flight software in the SCC will execute the algorithms for attitude determination and control system. This activity generates the relatively coarse estimates of position, attitude and rate.

6.5 Bus 10 Hz Events

At 100 millisecond intervals, the SCC commands the SIRU, Instrument Star Tracker, Laser Reference System, and Bus Star Trackers for data samples. The precise timing correlation for each data sample will be described below.

6.5.1 Space Inertial Reference Unit (SIRU)

The SIRU has a 16 bit timer (with an accuracy of 64 μsec) which is reset to zero only when the SIRU is initially powered on. This timer rolls over after 4.194 seconds. This time is not used by the SCC, GLAS, or the ground. The SIRU stores the gyro data in a buffer, including its internal counter value at a 100 Hz rate. The SCC time tags and requests updated accumulated angle information at a 10 Hz rate. The SIRU integrated angle has a BVTCW time stamp with a latency of 10 msec or less. All of the SIRU samples and their associated BVTCW time stamps are collected and put into the PRAP packet (10 Hz).

Reconstruction to GPS: SIRU data cannot be directly reconstructed to the GPS time scale because it has a latency of 10 milliseconds or less with respect to its associated BVTCW time stamp. The latency will create an effective pitch bias which will be removed as a normal part of science processing. The received GPS time is $GPSTime_{0.1}$ at $BVTCW_{0.1}$. Until the next GPS Timing pulse, compute:

$$SIRUSampleTime = GPSTime_{0.1} + (BVTCW_{SIRUSample} - BVTCW_{0.1}) * 1.0e\text{-}6 + latency$$

The latency is a solved-for factor, and the 1.0e-6 constant the PEC clock rate of 1 MHz.

6.5.2 Bus Star Trackers

Under nominal conditions and after initialization of the SCC and both tracker processors, the SCC issues regular 10 Hz data requests to both trackers. The flight software retains the lowest 32 bits of the BVTCW at the time it requests data with an accuracy of 5 μsec. The CCD images of the tracked stars are integrated over a time interval centered about a point ~124 msec (with an accuracy of 64 μsec) before the start of the ADCS cycle in which the data is used. This is the latency of the star tracker data. The lowest 32 bits of the BVTCW, the star tracker centroid data as well as the latency above is provided at 10 Hz in the PRAP packet.

Reconstruction to GPS: BST data is not normally used in science processing. It is expected to be used, however, to characterize the thermomechanical properties of the observatory, and will be used as a backup in case of a failure of the ROSI Instrument Star Tracker.

6.5.3 Instrument Star Tracker

The IST data output is synchronized with a 10 Hz timing pulse received from GLAS. The SCC sends the BVTCW to the IST at 1 Hz. The IST software resets the internal timer (20 μsec resolution) to zero upon receipt of the BVTCW. The IST returns the following to the SCC:

- The IST centroid data,
- The last BVTCW time received,
- The time from the BVTCW receipt to the last GLAS sync. pulse
- The Center of Integration (COI) is the time it takes from receipt of the GLAS sync pulse until output data has been integrated and it is nominally 51.088 ms, but can vary on occasion.

This data can be used to correlate BVTCW and GVTCW time to each other, which can then be related to GPS Receiver Time. The BVTCW and the IST centroid data are provided at 10 Hz in the PRAPacket. The COI time is provided in the PRAPacket at 1 Hz.

The LRS functions in the same manner, except that the COI is commandable and therefore does not have a constant value. The COI is measured and telemetered.

Reconstruction to GPS: The objective is to determine the COI time on the GPS time scale. The procedure is as follows (see Figure 5):

1. Convert the BVTCW to GPS time (see Section 6.2)
2. Add Δt_{BVTCW} to the GPS time of the BVTCW to create the estimated 10 Hz synch time.
3. Scan the shot timing data (see section 6.8.1) to identify the laser fire time within 12.5 msec of the estimated 10 Hz synch time. The laser fire time has a precise GPS time via its time stamped GVTCW, and will correspond to the precise 10 Hz External Synch.
4. Compute the COI time by adding the Δt_{COI} to the GPS time of the selected laser fire time.

Note that the resolution of the clock in the IST is 20 μsec.

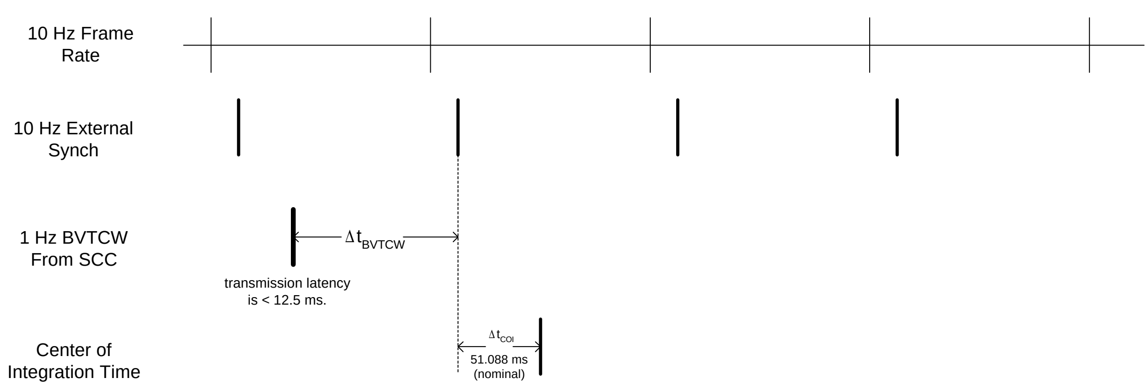

Figure 5 Instrument Star Tracker Timing

6.5.4 Laser Reference Sensor

The Laser Reference Senor functions in the same manner as the IST, except that the COI is commandable and therefore does not have a constant value. The COI is measured and telemetered.

6.6 GLAS 0.1 Hz Events

The GLAS MEU will time stamp the receipt of the 0.1 Hz GPS Timing pulse with the GVTCW at the time of the pulse. Shortly after the receipt of the GPS Timing pulse, the GLAS MEU will receive from the Time and Position packet (see 6.3.3.).

Reconstruction to GPS: The GPS system time is $GPSTime_{0.1}$ at $GVTCW_{0.1}$. Until the next GPS Timing pulse, compute:

$$GPSTime = GPSTime_{0.1} + (GVTCW - GVTCW_{0.1}) * 64.0e\text{-}9 + d$$

where the constant 64.0e-9 reflects the clock rate of 15.625 MHz derived from the Master Oscillator. δ is a measured value that accounts for the delays between the generation of the pulse at the GPS receiver and the time the pulse is latched.

6.7 GLAS 1 Hz Events

The GLAS MEU will capture the Time and Position packet sent from the SCC over the 1553 bus. The position data, updated every second by the SCC, is used by GLAS to update the position on the internal digital elevation map (DEM). Knowing the position on the DEM then permits the determination of the minimum and maximum ranges which are used to compute the range gate value.

The fields containing BVTCW (words 21,22 and 23) and GPS (words 19 and 20) time values of the last GPS time pulse are transferred to the next Ancillary Science Packet to be generated. They are updated only every 10 seconds, and the values of the two fields transmitted the other nine seconds are repeats.

Reconstruction to GPS: The value of the BVTCW field is $BVTCW_{0.1}$ for the 10 second interval. This value together with the GPS time and the $GVTCW_{0.1}$ also in the Ancillary Science Packet permits the synchronization of the GPS, GLAS and bus time schemes.

6.8 GLAS 10 Hz Events

At 100 millisecond intervals, the GLAS MEU will deliver a synchronization pulse to the IST and the LRS. This pulse is driven by the GLAS Master Oscillator and Counter. See section 6.5.3 for details.

6.9 GLAS 40 Hz Events

At 25 millisecond intervals, the GLAS MEU performs the following:

- Laser Fire and Time Stamp
- Time Stamp Fire Acknowledge
- Capture Altimeter Channel Data Sample
- Capture Cloud Channel Data Sample
- Capture Aerosol Channel Data Sample
- Capture LPA Data Sample

Details for each of the events are described in the following.

6.9.1 40 Hz Fire Command and Time Stamp

The 40 Hz Fire Command is triggered by the 40 Hz clock derived from the 2 GHz master oscillator. The command is time stamped by a 40-bit latch fed by a 40-bit counter which is driven by the 15.625 MHz clock. All the clock distribution logic is synchronous with negligible delays.

Reconstruction to GPS: The GPS system time is $GPSTime_{0.1}$ at $GVTCW_{0.1}$. Until the next GPS Timing pulse, compute the time of a 40 Hz Fire Command as:

$$40HzFireTime = GPSTime_{0.1} + (GVTCW_{40HzFire} - GVTCW_{0.1}) * 64.0e\text{-}9 + D$$

where the constant 64.0e-9 reflects the clock rate of 15.625 MHz derived from the Master Oscillator. Δ is a measured value that accounts for the time between the issue of the Fire Command and the time the Fire Command pulse is latched.

6.9.2 Fire Acknowledge Time Stamp

The Fire Acknowledge is time stamped by a 40-bit latch fed by a 40-bit counter which is driven by the 15.625 MHz clock. All the clock distribution logic is synchronous with negligible delays.

Reconstruction to GPS: The GPS system time is $GPSTime_{0.1}$ at $GVTCW_{0.1}$. Until the next GPS Timing pulse, compute the time of a Fire Acknowledge signal as:

$$FireAcknowledgeTime = GPSTime_{0.1} + (GVTCW_{FireAck} - GVTCW_{0.1}) * 64.0e\text{-}9 + Dfa$$

where the constant 64.0e-9 reflects the clock rate of 15.625 MHz derived from the Master Oscillator. Δfa is a measured value that accounts for the time between the issue of the Fire Ack and the time the Fire Ack pulse is latched.

6.9.3 Altimeter Digitizer Data Sample

The A/D converter for the Altimeter Digitizer is driven by the 1 GHz clock derived from the GLAS 2 GHz Master Clock.

Reconstruction to GPS: The GPS system time is $GPSTime_{0.1}$ at $GVTCW_{0.1}$. Until the next GPS Timing pulse, compute the time of an Altimeter Channel Data Sample as:

$$AltChanSamp = GPSTime_{0.1} + (GVTCW_{40HzFire} - GVTCW_{0.1}) * 64.0e\text{-}9 + index * 1.0e\text{-}9 + Dd$$

Where the index, a value ranging from 0 to 2^{24}-1, refers to the sample count beginning from the 40 Hz Fire Command, the constant 64.0e-9 accounts for the 15.625 MHz clock signal feeding the Master Counter, and the constant 1.0e-9 accounts for the 1 Gsample/sec operation of the altimeter digitizer. Δd is a measured valued that accounts for the delay between the 40 Hz Fire Command and the start of the digitizer.

6.9.4 Cloud Digitizer Data Sample

The A/D converter for the Cloud Channel is driven by the 2 MHz clock derived from the GLAS 2 GHz Master Clock. The gating on of the sampling bins is determined by the estimate of the spacecraft-to-ground range which is provided by the DEM in GLAS for the current spacecraft position.

Reconstruction to GPS: The GPS system time is $GPSTime_{0.1}$ at $GVTCW_{0.1}$. Until the next GPS Timing pulse, compute the time of a Cloud Channel Data Sample as:

$$CDSample = GPSTime_{0.1} + (GVTCW_{40HzTime} - GVTCW_{0.1}) * 64.0e\text{-}9 + Df + Dc$$

The constant 64.0e-9 reflects the clock rate of 15.625 MHz derived from the Master Oscillator. $GVTCW_{40HzTime}$ is GVTCW for either the 40 Hz Fire Command or the Fire Ack signal (selectable by ground command). Δf is a measured valued that accounts for the delay between the 40 Hz Fire Command or the Fire Ack signal and the start of the digitizer. Δc is the value of the commandable delays: Background #1, Background #2, or Range Gate. These three values are reflected in the ancillary science packet.

6.9.5 Aerosol Channel Data Sample

The A/D converter for the Aerosol Channel is driven by the 2 MHz clock derived from the GLAS 2 GHz Master Clock.

Reconstruction to GPS: The received GPS time is $GPSTime_{0.1}$ at $GVTCW_{0.1}$. Until the next GPS Timing pulse, compute the time of a Aerosol Channel Data Sample as:

$$AerosolChanSample = GPSTime_{0.1} + (GVTCW_{40HzTime} - GVTCW_{0.1}) * 64.0e\text{-}9 + Df + Dc$$

The constant 64.0e-9 reflects the clock rate of 15.625 MHz derived from the Master Oscillator. $GVTCW_{40HzTime}$ is GVTCW for either the 40 Hz Fire Command or the Fire Ack signal (selectable by ground command). Δf is a measured valued that accounts for the delay between the 40 Hz Fire Command or the Fire Ack signal and the start of the photon counter. Δc is the value of the commandable delays: SPCM Gate, Background #1, Background #2, or Range Gate. These four values are reflected in the ancillary science packet.

6.9.6 Capture LPA Data Sample

The precise time of the data captured by the LPA is related to the 40 Hz Fire Command Time time stamp via the shot counter values in the LPA and Ancillary Science packets.

Reconstruction to GPS: The received GPS time is $GPSTime_{0.1}$ at $GVTCW_{0.1}$. Until the next GPS Timing pulse, compute the time of a Aerosol Channel Data Sample as:

$$LPASample = GPSTime_{0.1} + (GVTCW_{40HzFire} - GVTCW_{0.1}) * 64.0e\text{-}9 + Df$$

The constant 64.0e-9 reflects the clock rate of 15.625 MHz derived from the Master Oscillator. $GVTCW_{40HzFire}$ is GVTCW for the 40 Hz Fire Command. Δf is a measured valued that accounts for the delay between the 40 Hz Fire Command and the sample time of the CCD in the LPA.

Appendix A - Definitions

This section presents a set of definitions for the precise timing related functions on the GLAS instrument and the RS2000 bus.

A. GLAS Terms

- *Master Oscillator*: A 2 GHz oven controlled oscillator in GLAS. For redundancy, there are two master oscillators. Each oscillator is dedicated to its own altimeter digitizer board. They are not cross-strapped.
- *Master Counter*: A 40-bit counter driven at 15.625 MHz which is derived from the Master Oscillator. The counter roll over time is approximately 19.5469 hours.
- *40 Hz Fire Command*: An electrical signal issued by the Main Electronics Unit (MEU) by the software in the Instrument Processor System (IPS). The signal is issued upon detection of an interrupt derived from the Master Oscillator and issued by a downcounter at 40 Hz. The 40 Hz Fire Command is sent to the operating laser, the Laser Profiling Array, the altimeter digitizer, cloud digitizer, and photon counter boards. When divided by 4, it is also sent to Stellar Reference System in the form of a 10 Hz synchronization pulse.
- *40 Hz Fire Command Latch*: This is a 40-bit latch circuit that captures the value of the Master Counter when the 40 Hz Fire Command signal is issued. This is reported for each laser firing in the Ancillary Science Packet.
- *Fire Acknowledge*: An electrical signal that is sent from the laser to the GLAS Main Electronics Unit where it is latched. This signal is also sent to the altimeter digitizer, cloud digitizer, and photon counter boards.
- *Fire Acknowledge Latch*: This is a 40-bit latch circuit that captures the value of the Master Counter when the Fire Acknowledge signal is issued. This is reported for each laser firing in the Ancillary Science Packet.
- *GPS Timing Pulse*: The pulse issued once per 10 seconds over the RS-422 interface from the one of the two GPS receivers. Only one receiver is active at any time.
- *GPS Timing Pulse Latch*: This is a 40-bit latch circuit that captures the value of the Master Counter when the GPS Timing pulse signal is received from a GPS receiver. This is reported in the Ancillary Science Packet.
- *GLAS Vehicle Time Code Word (GVTCW)*: This is the value of one of the GLAS 40-bit latch circuits when it records a 40Hz Fire Command, Fire Acknowledge, or a GPS timing pulse at a specific time. The range of values of the GVTCW represent a stable, accurate timing scheme that can be related to GPS time.
- *Shot Counter*: A counter that generates an integer number from 0 to 199 which identifies individual shots. This counter is derived from the Master Counter. The original function of this counter was to count shots for SRS data tagging. This function is no longer necessary; however, the counter remains in order to correlate data between GLAS science packets.
- *10 Hz Timing Pulse*: This signal is derived from the Master Oscillator and issued by the MEU to the Instrument Star Tracker (IST) and the Laser Reference System(LRS). It is used by both the IST and LRS as a synchronization signal to precisely timestamp the center of integration time.

B. Bus Terms

- *Precision External Oscillator (PEC)*: An oven controlled oscillator (OCXO) on the Bus that drives a 48-bit counter and latch circuit in the Spacecraft Control Computer (SCC). The counter roll over time is approximately 8.9255 years.
- *Bus Vehicle Time Code Word (BVTCW)*: This is the value of the 48-bit counter sampled by the 48-bit latch circuit when the SCC time tags an event such as the GPS Timing Pulse. The range of the BVTCW represents a stable, accurate timing scheme that can be related to GPS time. All non-real-time spacecraft commands are time-tagged in terms of BVTCW. BVTCW will reset to zero upon power up/reset.
- *Bus UTC (BUTC)*: A time scheme used by the SCC when running the on-board orbit propagator that is used for determining position in the magnetic field strength map and also predicting the sun position. BUTC is derived from BVTCW by multiplying a conversion factor times the current value of the BVTCW and adding it to the value of UTC when the BVTCW was last reset to zero. In sum, BUTC is used only for low accuracy housekeeping functions internal to the bus and is found nowhere else in the Observatory.

Appendix B - Data Packet Flow and Timestamp Relationships

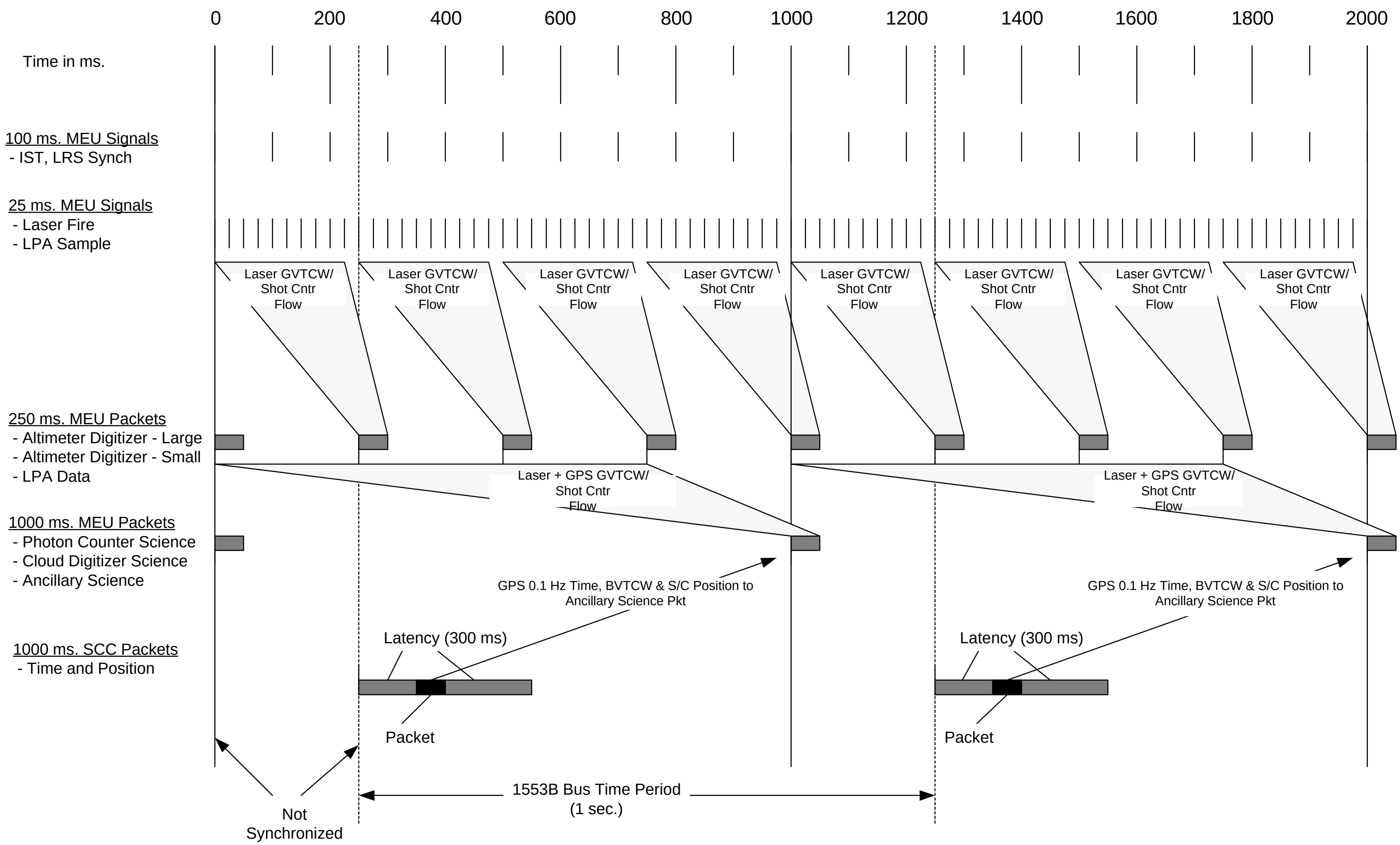

Figure B-1: GLAS MEU Packets and Timing

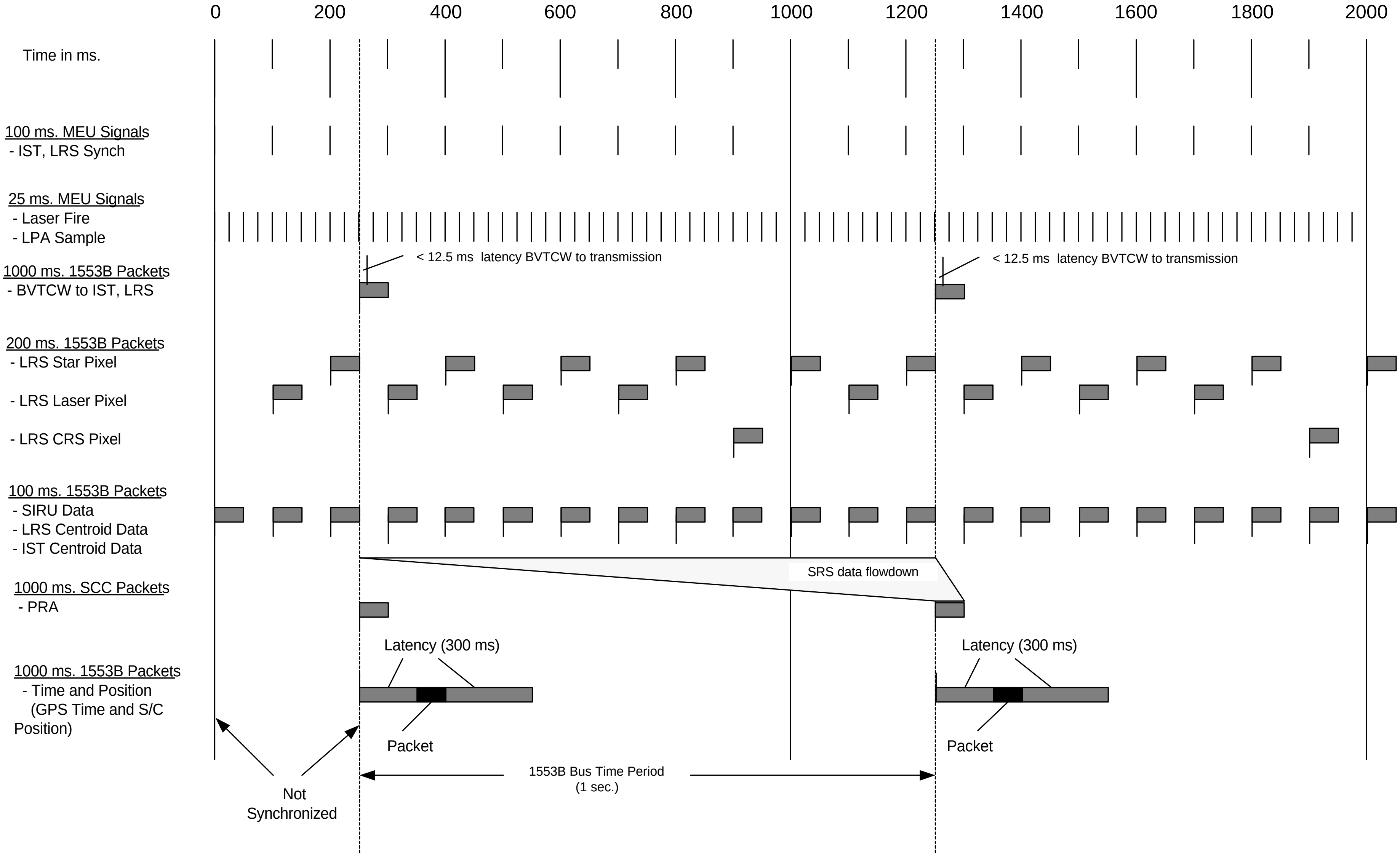

Figure B-2 : SRS Packets and Timing

Appendix C - Timing Validation and Verification

To be provided